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Teramobile Laser and Lightning

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Final Report

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14. ABSTRACT
An ultrashort, terawatt laser was used to trigger lightning by creating ionized path in atmosphere. Joint French-German Teramobile was brought to the Langmuir Laboratory for Atmospheric Research for the experiment. Arrays of instruments were used to assess lightning initiation, or ionized path to perturb the local electric field. No lightning discharges were observed triggered by the laser, but good understanding of physics and future laser needs were determined.

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1 Introduction

For the past forty years researchers have been able to trigger lightning by rapidly inserting conductors into the high-field regions below thunderstorms. Generally these conductors have been thin wires pulled up by small rockets. Under the right conditions, the highly intensified field at the tip of the wire is strong enough to produce a leader that can propagate into charge regions of the thunderstorm and initiate a lightning discharge. If it were possible to develop a method to trigger lightning without the disadvantages of rockets and wires, such a method might sometimes be able to protect facilities by usurping natural lightning with triggered lightning and thereby directing the high currents to locations where no damage will result.

One proposed mechanism for triggering lightning is the use of a high-powered laser to produce a conductive ionized path in the atmosphere. To test this idea the Teramobile, a high-power laser, was brought to the Langmuir Laboratory for Atmospheric Research to attempt laser triggering of lightning. Langmuir Laboratory was chosen for two reasons: (1) Lightning has been triggered many times over Langmuir Laboratory by metal wires pulled up by small rockets, and (2) Langmuir Laboratory has an array of instruments that can be used to determine if the laser initiates lightning, or produces an ionized path which is sufficiently conductive to perturb the local electric field. The instruments include electric field mills, an electric field change meter (slow antenna), a Lightning Mapping Array (which generates 3-dimensional images of lightning discharges) and several video cameras.

The Teramobile attempted to trigger lightning many times when the fields were strong enough that rocket-triggered lightning would probably have been effective. No lightning discharges were observed to be triggered by the laser, nor was there any evidence that the laser produced an ionized path sufficiently conductive to perturb the local electric field.

2 Location

Langmuir Laboratory for Atmospheric Research is located in a U. S. National Forest at an elevation of 3200 m above sea level along the main north-south ridge of the Magdalena Mountains west of the town of Socorro in central New Mexico. The mountains are an elevated heat source, which initiates thunderstorms during the summer monsoon season. When the winds are low, the thunderstorms go through their entire life cycle over the mountains, so that it is possible to study entire thunderstorms at a fixed location.

3 Instruments and Methods

3.1 Teramobile

The Teramobile laser emits brief, high-power pulses at a rate of 10 pulses each second. Each pulse emits light with a wavelength of 800×10^{-9} m (infra-red) with an energy of 0.35 J lasting for 70×10^{-15} seconds. During the pulse the power is 5×10^{12} watts. More details of the Teramobile can be found in an article by *J. Kasparian et al.* [2003].

The Teramobile was housed in the Balloon Hangar at Langmuir Laboratory, which is 3200 m above sea level at latitude N33^o 58.92421' and longitude W107^o 11.28727'. Figure 1 shows the Teramobile inside of the Balloon Hangar. Between the top of the Teramobile and the top of the Balloon Hangar, a 200 mm diameter fiberglass tube at an angle of 70^o above horizontal surrounded the laser beam in order to avoid any inadvertent diversion of the beam into the Hangar. The tube extended through the roof and above the Balloon Hangar about 1.5 m; a semi-cylinder continued about 1 meter above the top of the tube to keep hail and rain from entering the tube.

In tests at Langmuir Laboratory with the laser beam aimed horizontally near the ground, filaments of ionized air appeared between 30 m and 200 m distant from the laser source.

A mechanical shutter in front of the laser allowed the pulses to penetrate the atmosphere for intervals of a few seconds separated by dark intervals of a few seconds. The shutter times were recorded in a log file kept by a Teramobile computer.

Figure 1. Photograph of the Teramobile inside the Balloon Hangar at Langmuir Laboratory. Part of the tube that shields the laser beam and deflects rain and hail is visible between the top of the Teramobile container and the inside of the roof of the Hangar. Photograph courtesy of Harald Edens of New Mexico Tech.

3.2 Electric Field Meters

Electric field meters near the Balloon Hangar and at two other locations about 1 km in opposite directions provide a record of the development of the electric field below a storm and have been used to give an indication of the most likely times for triggering lightning by rockets that haul up metal wires. Electric field amplitudes greater than about 12 kV/m are sufficient for triggering lightning at the top of South Baldy Peak. Lower amplitudes—perhaps 10 kV/m or less—are sufficient for triggering lightning elsewhere along the ridge.

3.3 Electric Field-Change Meters

Electric Field-Change Meters (also known as slow antennas) effectively record the electric field after it has passed through a high pass filter. Such an instrument was operated near the Balloon Hangar. We had thought that it might be able to detect small movements of electrical charge along the laser beam in cases where the laser beam did not trigger lightning. However, the movement of large charges in the distance by natural lightning masked the movement of any small charges that might have been transported along the conducting filaments of the laser beam.

3.4 Television Cameras

Triggered and natural lightning cannot easily be distinguished using electric field meters or electric field-change meters; both kinds of lightning cause sudden changes in the signals. A prominent characteristic of triggered lightning is that it has a straight section, which is caused by lightning currents following the triggering wire or, perhaps in this case, a laser-induced filament. One good way to establish the existence of triggered lightning is to visually observe this straight section or to capture the image with a television camera.

Television cameras were operated in the main Langmuir building and at its Annex nearby. The images of the cameras were recorded on hard disks. Observers in the Annex were also present during laser operation.

Television cameras and observers require good visibility. One of the storms over the Laboratory during the operation of the Teramobile (starting on September 25, 2004) engulfed the Balloon Hangar and all the other facilities along the Magdalena Ridge, reducing visibility. During this storm, some of the time intervals between the scattered light from lightning and thunder heard at the Balloon Hangar were one second or less, indicating that natural or triggered lightning were within a few hundred meters of the Balloon Hangar. In the absence of clear visibility, the best, but not perfect, way to distinguish between natural and triggered lightning is to use data from the Lightning Mapping Array.

3.5 Lightning Mapping Array (LMA)

The Lightning Mapping Array (LMA) around Langmuir Laboratory is an array of radio receivers that record the times of pulses generated by lightning. Using the Global Positioning System (GPS) as a clock, the times at each receiver are recorded with a precision of about 40 nanoseconds. The amplitudes of the pulses are also recorded. The three-dimensional locations and times of lightning sources are reconstructed with computers by searching for sets of pulses from the different receivers that could have come from a single source.

Some lightning processes do not emit pulses detectable by the Lightning Mapping Array. In particular, positive leaders, which propagate into regions of negative charge, can be invisible to the Array because they emit weakly [*Stanley et al*., 1994; *Krehbiel, et al*., 1994]. Most triggered lightning begins with a positive leader that propagates upward from the top of the triggering wire and so might be difficult for the LMA to see. However, when triggering is done with a wire not connected to ground, the positive leader propagating upward from the top of the wire will be accompanied by a negative leader propagating downward from the bottom of the wire to complete the path to ground, and the negative leader will emit detectable pulses. In the case of the laser, since the filaments in the laser beam do not extend all the way to ground, the pulses from downward-propagating negative leaders should be detectable. In addition, dart leaders that later propagate from the cloud down the initial positive leader channel may also emit detectable pulses, and thus the initiation of triggered lightning by laser filaments should be detectable by the Lightning Mapping Array.

The Lightning Mapping Array can also distinguish between natural and triggered lightning by establishing the location of the place where lightning begins. Clearly, lightning that begins far from the triggering area is not triggered.

The design of the Lightning Mapping Array is described by *Rison, et al*. [1999]; *Thomas, et al*. [2004] describe the accuracy of the Array.

4 Overview of storms

The Teramobile was moved into the Balloon Hangar at Langmuir Laboratory on July 31,2004. Triggering attempts began on August 13 and continued through the storm that began on September 25 and ended on September 26 UTC. The Teramobile was transported from the Balloon Hangar at Langmuir Laboratory to the New Mexico Tech campus on October 7, 2004. Subsequently, it was transported to Albuquerque, New Mexico.

The following paragraphs describe briefly all the daytime storms from August 13 to September 26 during which the $|E|$ had a peak value greater than about 2 kV/m. This overview relies mainly on data from the electric field sensor at the ground near the Balloon Hangar because $E(t)$ is the most useful indicator of when lightning might be triggered by wires hauled up behind rockets and, presumably, by the laser as well.

In the past, several groups have triggered lightning from various locations along the ridge and mountain peak where the Laboratory facilities are located. The triggering location with an altitude and exposure most similar to those at the Balloon Hangar is at the base of South Baldy Peak. This location is now known as the GWEN site; a receiver in the Lightning Mapping Array is now located there.

In 1981 *Hubert et al*. [1984] triggered lightning 35 times with wires hauled up by small rockets at the GWEN site. For comparison with the graphs of $E(t)$ below, *Hubert et al*. estimated that E>9 kV/m is generally a sufficient condition for triggering lightning, but the value is affected by other factors. *Hubert et al*., [1984], also give a relation between the electric field E (in kV/m) at the ground and the height H (in meters) of the rocket when triggering occurred:

$$H=3099E^{-1.33} \quad . \tag{1}$$

Using this equation, when E=10 kV/m, H=168 m, which is less than the length of the laser filaments.

Our sign convention in the graphs of $E(t)$ below is as follows: an electric field at the ground is said to be positive when the electric vector is pointed upward, which is when the electric field is dominated by negative charge overhead. All of the lightning flashes triggered by *Hubert et al*. occurred when E was positive by our sign convention (and negative by his sign convention), that is, when negative charge overhead dominated the electric field at the ground.

- **August 13.** The electric field *vs*. time at the ground near the Balloon Hangar is shown in Figure 2. From 22.5 to 23.1 hours UTC, lightning *increased* the magnitude of the electric field, $|E|$, resulting in brief times when the field at the Balloon Hangar was abnormally high, and triggering might have been possible. An expanded view of the interval time when lightning increased $|E|$ and the laser was operating is shown in Figure 3. This storm is treated in more detail in the next section.

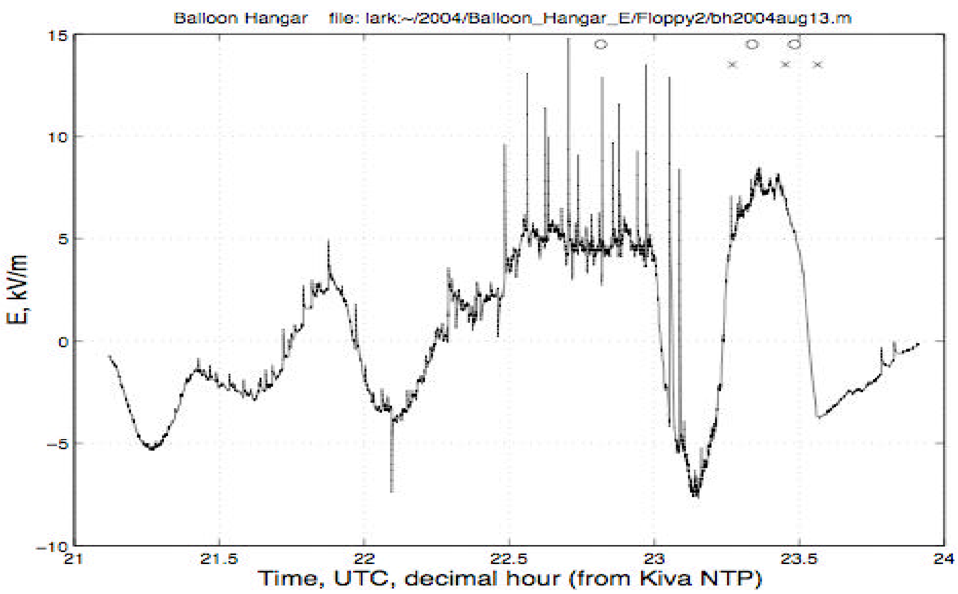

Figure 2: Electric Field at the Balloon Hangar on 2004 August 13. The small circles above the electric field trace are the times when the laser shutter is opened. Nearby, the letter 'x' denotes times when the laser shutter is closed. Sudden discontinuities in $E(t)$ are caused by lightning flashes.

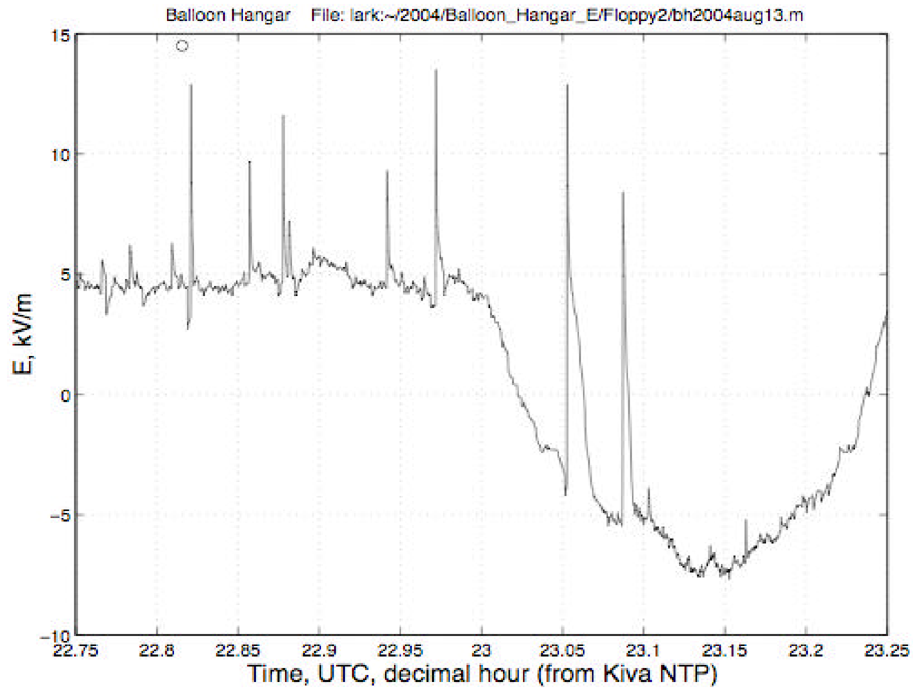

Figure 3: An expanded view of a portion of the previous figure.

- **August 14**. $|E|<5.5$ kV/m during the entire storm. Lightning decreased the amplitude of the electric field and/or changed its sign from positive to negative. Laser triggering was not attempted.
- **August 15**. $|E|<5$ kV/m during the storm and there was no nearby lightning. Laser triggering was not attempted.
- **August 16**. $|E|<7.5$ kV/m. The laser emitted pulses.
- **August 17**. $|E|<6$ kV/m. Laser triggering was not attempted.
- **August 18**. $|E|<7.5$ kV/m except briefly just after four lightning flashes. After three of the flashes $|E|\approx 10$ kV/m, and after the fourth flash $|E|>15$ kV/m, when triggering might have been possible. The laser emitted pulses.
- **August 19**. $|E|\approx 7$ kV/m during its maximum, but there was no nearby lightning. Laser triggering was not attempted.

- **August 20**. $|E|<3$ kV/m during a storm that made frequent lightning in the distance. Laser triggering was not attempted.
- **August 21**. $|E|<7$ kV/m and there were no nearby lightning flashes. The laser emitted pulses.
- **August 23**. $|E|<6$ kV/m. There were no operations.
- **August 24**. $|E|<5$ kV/m. Laser triggering was not attempted.
- **August 29**. $|E|<8$ kV/m except briefly after one lightning flash, when $|E|\approx 11$ kV/m. There were numerous lightning flashes. The laser emitted pulses.
- **August 30**. $|E|<7.5$ kV/m except briefly after one lightning flash when $E\approx 8$ kV/m. This was a weak storm with few lightning flashes. The laser emitted pulses.
- **August 31**. $|E|<5$ kV/ m. There were two distant lightning flashes. There were no triggering attempts.
- **September 1**. $|E|<8.5$ kV/m. There were no triggering attempts.
- **September 2**. $|E|<4.5$ kV/m. There were no triggering attempts.
- **September 4**. $|E|<7$ kV/m. There were no triggering attempts.
- **September 5**. $|E|<7$ kV/m. There were no nearby lightning flashes. There were no lightning triggering attempts.
- **September 9**. Large positive excursions of E at the Balloon Hangar this day were caused by the French TV crew waving charged strips of Teflon under the field meter. There were no other operations and no storms.
- **September 13**. Our forecasting was poor this day. The storm began before we arrived and we did not have the airspace required for laser emissions. $|E|\approx 9.5$ kV/m briefly twice, once just after a lightning flash increased the electric field amplitude. $E\approx 8$ kV/m for about 15 minutes. There were no triggering attempts.
- **September 18**. On this day there was another Teflon test of the electric field meter at the Balloon Hangar. In another experiment, the laser emitted pulses in a low electric field while a Le Croy oscilloscope that was attached to the field-change meter near the Balloon Hangar looked for perturbations in E that might be synchronized with the laser pulses; none were seen.
- **September 19**. $|E|<3.5$ kV/m. The Laboratory was in a thick cloud all day. There was no nearby lightning. A triggering window was open from 2225 to 2258 Z.
- **September 24** $E(t)$ at the Balloon Hangar is shown in Figure 4. This was a vigorous storm with nearby lightning flashes. The electric field at the Balloon Hangar was greater than 8 kV/m for a total of more than 13 minutes, and it was greater than 10 kV/m for more than 2.4 minutes. There were numerous lightning channels within 2 km of the main Langmuir buildings. Visibility was good along the ridge. The Teramobile attempted triggering during the active parts of the storm—from 2049 to 2219—except for some brief down times.

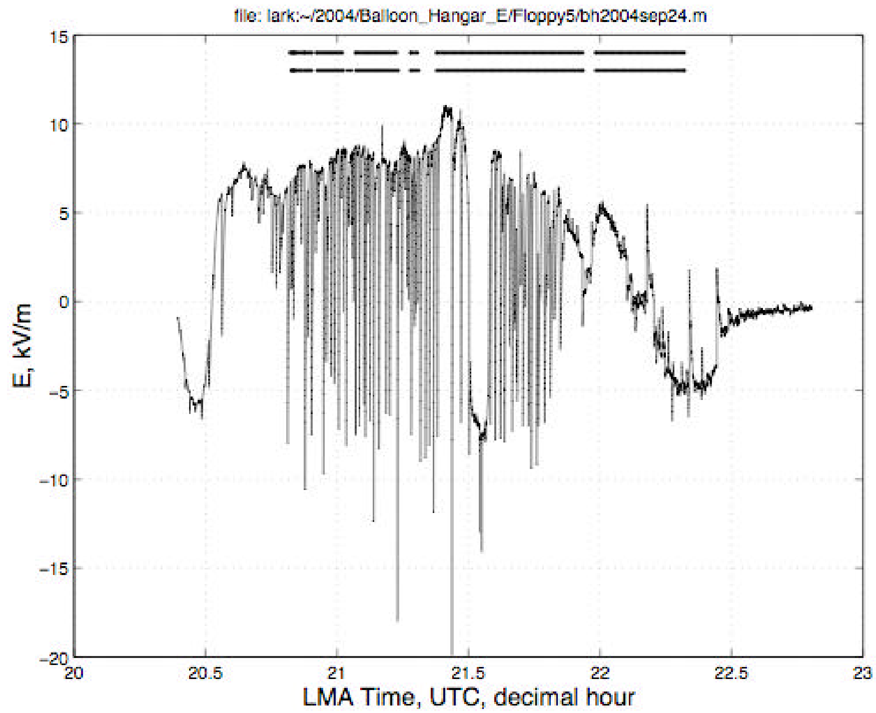

Figure 4: Electric field at the Balloon Hangar on September 24, 2004. The two rows of line segments above the $E(t)$ are unresolved dots. The upper row of dots indicates times when the laser shutter opened. The lower row indicates times when the laser shutter closed.

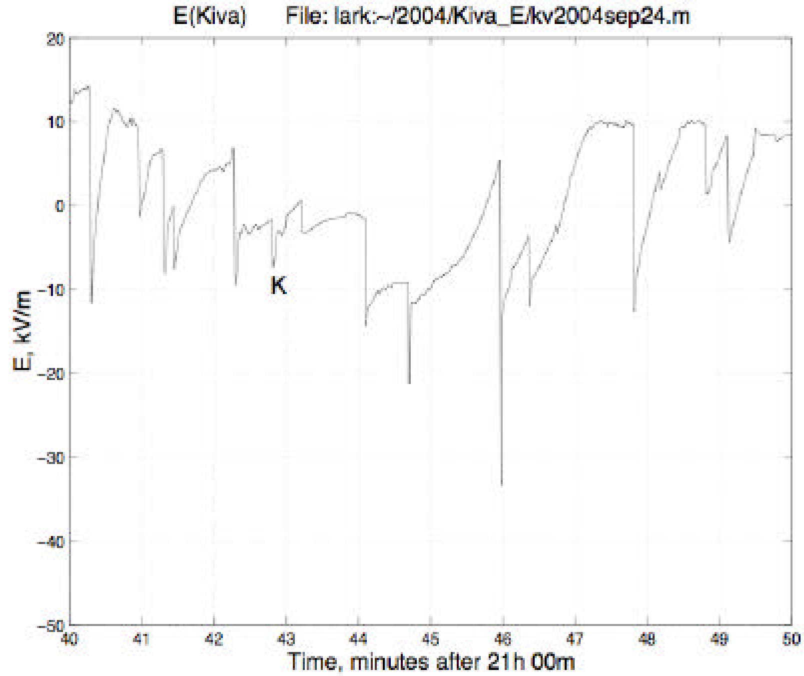

Figure 5: Electric field at Kiva II on September 24, 2004 during a 10-minute interval around the time when lightning struck the ground near Kiva II. The electric field discontinuity from the near strike is just above the letter 'K' on the graph.

Lightning struck ground near South Baldy Peak at 2142:48.6 UTC. This flash was in the field of view of a video camera at the Annex building, and there is a recording of it on a digital video disk. Figure 5 shows $E(t)$ from a sensor near Kiva II on South Baldy Peak. It is interesting to note that the electric field at the ground near the lightning strike point just before the lightning flash was about -2 kV/m instead of a large positive value.

The video camera at the Annex also shows another lightning flash that had two separate channels to ground, one to the north of the Balloon Hangar and another to the south of the Balloon Hangar.

- **September 25**. The electric field at the Balloon Hangar is shown in Figure 6. $|E|$>10 kV/m for more than 7.5 minutes at the Balloon Hangar and $|E|$>20 kV/m briefly after two lightning flashes. This was a vigorous storm lasting more than four hours. It was unusual in that the Laboratory was engulfed in the cloud; the cloud base was below the altitude of the Laboratory. Visibility was often as low as 50 to 100 meters. The storm produced hail and about 10 cm of snow. There were many lightning flashes, some close to the buildings. One flash struck an overhead ground wire on the Annex, vaporized much of it and produced glowing fragments that melted through the snow on the roof and scorched the paint below; this is probably the same flash (at 2317:27 UTC) that damaged an electric field meter at the Annex. Another flash (around 2322:55 UTC) tripped a circuit breaker that fed power from the main Langmuir Building to some of the trailers and buildings along the ridge, disabling the fiber optic link and consequently three of the LMA stations (Microphone Hill, West Knoll, and Balloon Hangar). Steve Hunyady, at the Balloon Hangar, reported a number of close flashes, judging from the time between the sudden diffuse light and the onset of thunder. Laser beam emissions continued for more than two and a half hours—from 2134 to 2418 with some brief recesses. An expanded view of part of Figure 6 is shown in Figure 7. The first flash in the latter figure, at 2352:44, increases the electric field at the Balloon Hangar to almost 20 kV/m; the evolution of this flash will be shown below in the section on results from the Lightning Mapping Array.

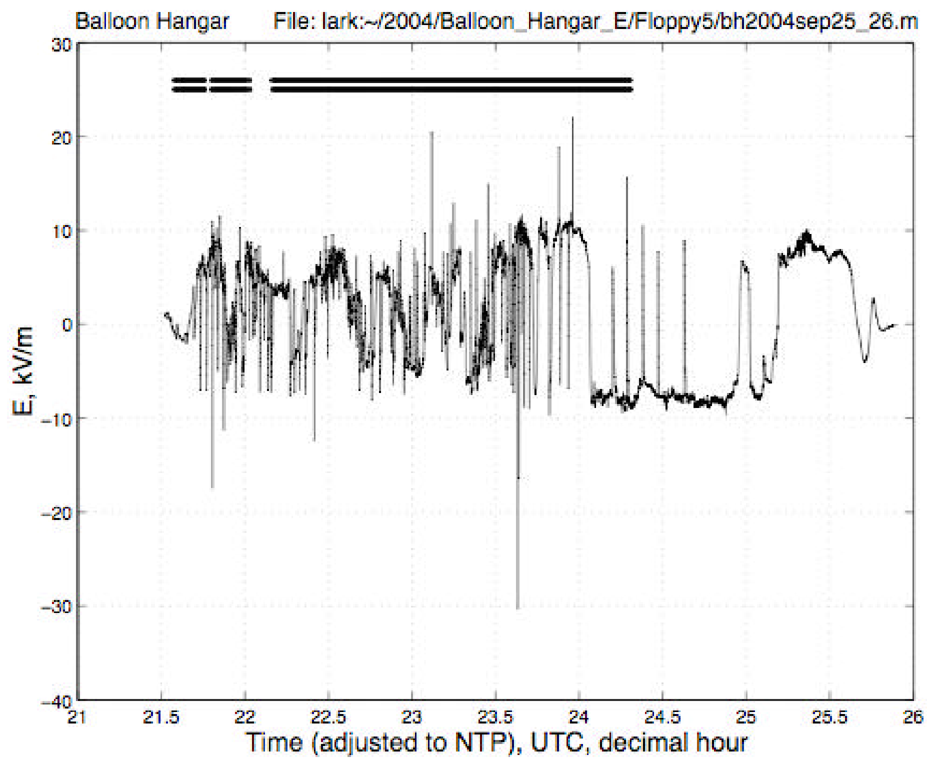

Figure 6: Electric field at the Balloon Hangar on September 25 and 26, 2004. Times greater than 24 hours are on September 26.

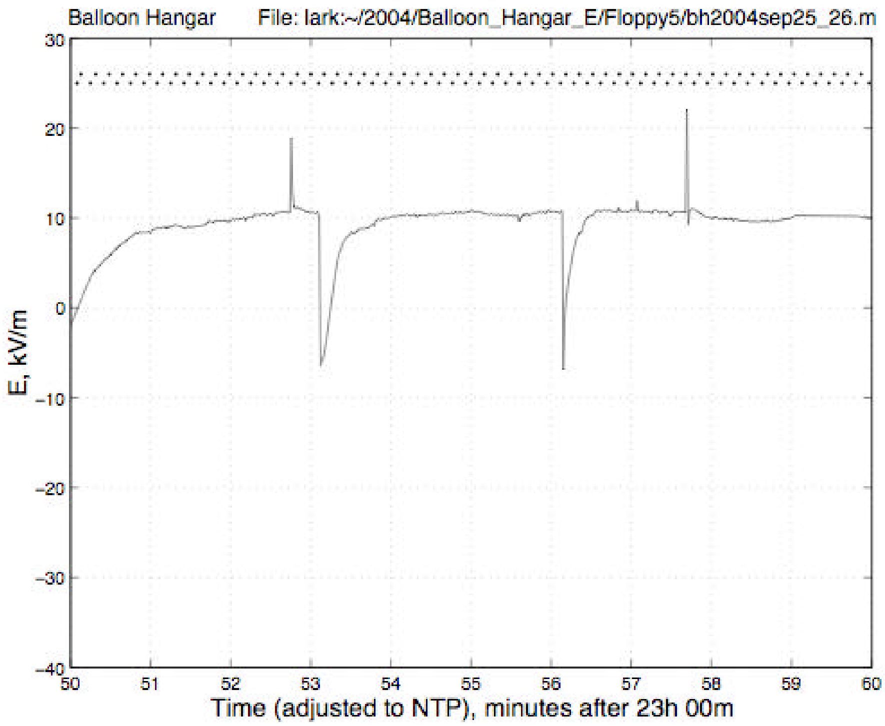

Figure 7: Expanded view of part of the electric field record from the Balloon Hangar on September 25, 2004.

5 Results from the Lightning Mapping Array

The examination of $E(t)$ at the Balloon Hangar in the previous section has been an attempt to assess the probability that lightning could have been triggered by rockets carrying up wires as in past experiments. The probability appears to have been good during several time intervals when E>10 kV/m on August 13, September 24, and September 25. The laser beam was propagating upward outside the Balloon Hangar during these time intervals. In this section, we address two questions:

1. Were any of the lightning flashes that occurred during laser operations actually triggered?
2. Did the laser filaments give rise to any minor leaders that did not develop into lightning flashes?

Usually, a rocket-triggered lightning flash is easy to detect. People are alerted by the countdown for the rocket firing and the bright lightning channel with a straight segment is usually easy to see. On the other hand, with laser triggering attempts, the laser beam is run for long times, often hours, and people do not watch all the time. A successful trigger could be missed.

Furthermore, one of the most interesting storms during the summer of 2004 at Langmuir Laboratory had a cloud base below the altitude of the triggering site, and visibility was often less than 100 meters.

To ascertain whether or not any nearby flashes were triggered by the laser and to search for minor discharges near the laser filaments, we examine where lightning originated and where it propagated using data from the Lightning Mapping Array for the three storms most likely to have been susceptible to triggering (the storms on August 13, September 24, and September 25).

5.1 August 13

Triggering might have been possible from 2230 to 2300 UTC during the storm on August 13 because the electric field (see Figure 8) increased to rather large values (greater than 10 kV/m) briefly after lightning flashes. The very rapid decline of these intense electric fields after lightning at the ground is largely because of the release of corona ions from pointed objects (e.g. the tops of bushes and trees) attached to the ground and the establishment of a corona space-charge layer above the electric field sensor. A few hundred meters above the ground, the electric field amplitude declines much less quickly (*Standler and Winn*, 1979), and triggering is possible for a longer period of time than is indicated by the decay of E at the ground if the triggering conductor penetrates above the layer of corona ions.

On this day, a radio transmitter on the southwest corner of the roof of the Balloon Hangar emitted 63 MHz pulses in response to a gating signal received from the Teramobile. The Lightning Mapping Array, which operates at 63 MHz, shows these pulses (see Figure 8); some of the pulses are misplaced above and below ground level, probably because the sources were weak and the only LMA receivers that detected them are near the same altitude.

Figure 8 also shows that there were no detectable RF sources near the upper end of the laser filaments. While the initial upward-moving positive leaders could have been missed because they radiate radio frequencies weakly, and RF sources that might have been coincident with the pulsing transmitter on the top of the Balloon Hangar probably would have been overshadowed by the transmitter, downward dart leaders, had they existed, might have been observed near or above the top of the filaments.

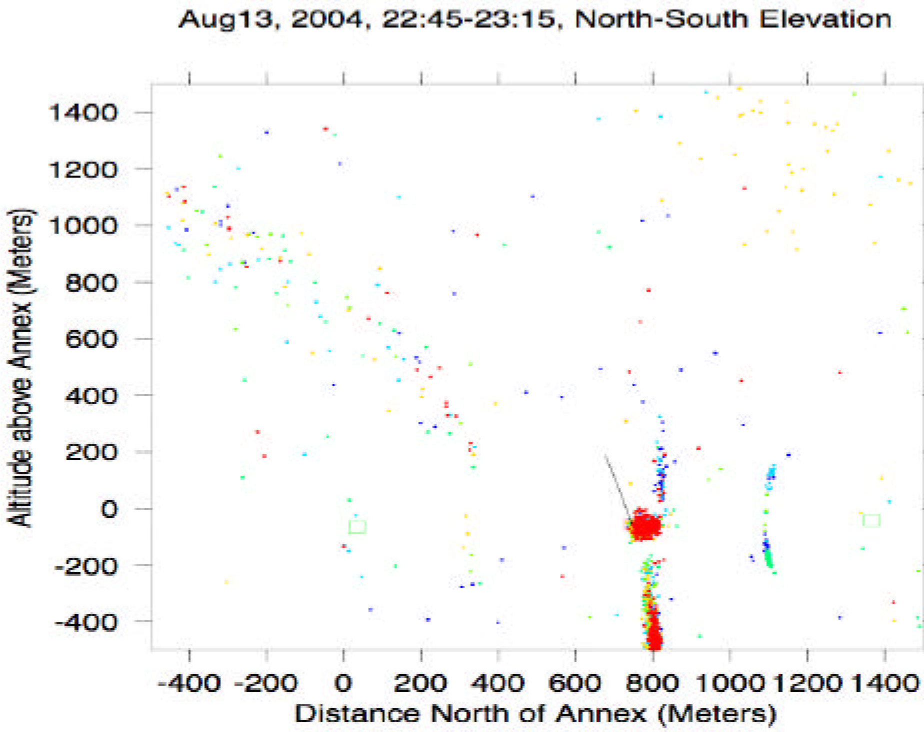

Figure 8: Radio frequency pulses centered at 63 MHz received by the Lightning Mapping Array from 2245 to 2315 UTC during the storm on August 13, 2004.

Some pulses emanating from the Balloon Hangar are placed at the wrong altitudes because of data processing errors. The location of the filaments in the laser beam is shown as a heavy black line angled 70 above the horizon. The squares are locations of LMA receivers (from south to north: Microphone Hill, Balloon Hangar, and GWEN). The Annex building is at the origin (0,0,0), near Microphone Hill; altitudes are relative to the Annex. To obtain the points on the graph, the largest amplitude signals in each 80µs interval at each receiver in the array are used to deduce the locations of sources. Then, only the sources inside a cubic volume 2 km on a side enclosing the Balloon Hangar are kept and projected onto a vertical plane in the north-south direction.

The best indication that the laser filaments did not trigger during this storm is that the lightning flashes indicated by discontinuities in the electric field record (Figure 8) did not originate near the Balloon Hangar. The next section, about the storm on September 24, shows how the place of initiation of lightning can be determined using the Lightning Mapping Array.

5.2 September 24

We examined RF lightning sources computed from LMA data for all the lightning flashes that came near the mountain ridge between the Langmuir Annex and South Baldy Peak (where the Kiva LMA receiver is located). No sequence of sources were detected by the Lightning Mapping Array that would suggest that lightning flashes were initiated by the laser filaments. Nor did the LMA detect any minor leaders emanating from the either end of the laser filaments.

There were, however, branches from natural lightning flashes that propagated over the Balloon Hangar. We present examples of these flashes because they are pertinent to the need to trigger to prevent damage.

Figure Figure 9 shows a flash that originated about 4 km northwest of the Balloon Hangar and then spread out in several directions. Several branches traveled near South Baldy Peak, where the Kivas are located, and caused the electric field to drop 30 kV/m. In contrast, at the Balloon Hangar, located about 1 km to the south, the electric field dropped only 2 kV/m.

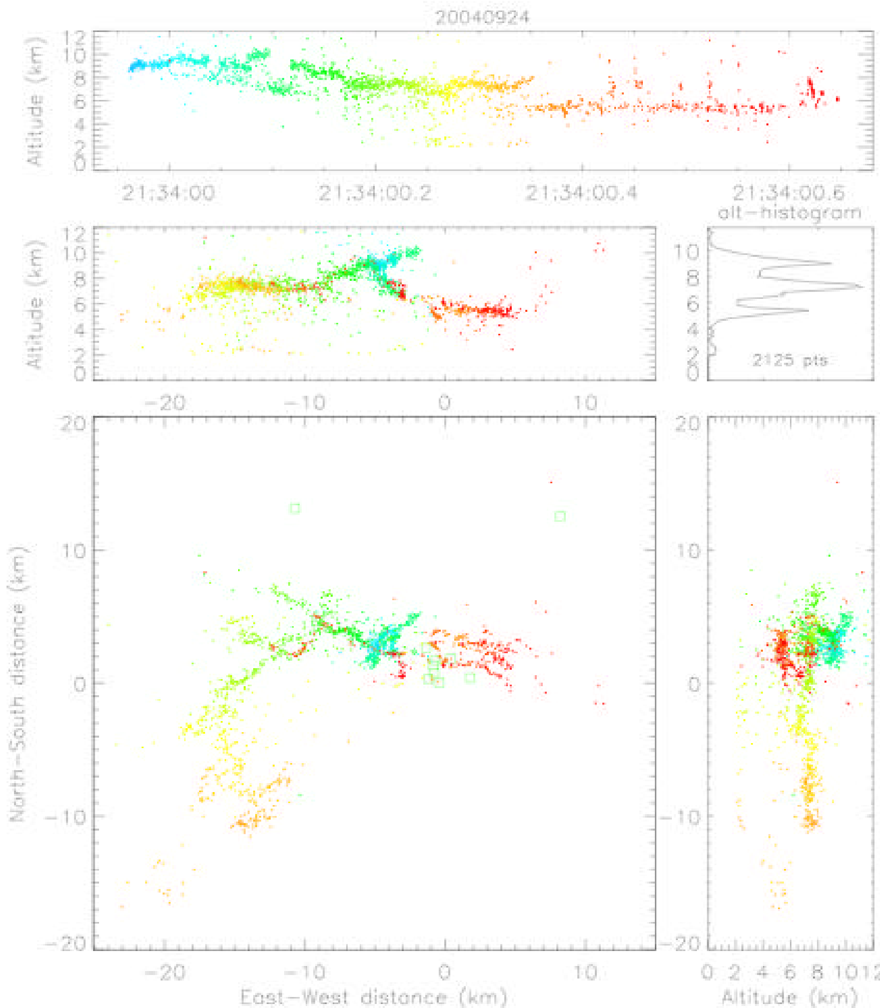

Figure 9: Lightning Flash that began at 2133:59 UTC on September 24, 2004. The cluster of small squares near the center of the lower-left panel show the locations of the LMA receivers on or near the mountain range where Langmuir Laboratory is located. The outlying receivers are off the mountain range, at lower altitudes.

Figure 10 shows a lightning flash that originated about 8 km southeast of the Balloon Hangar. A branch propagated directly over the Balloon Hangar, causing an electric field change of about 13 kV/m.

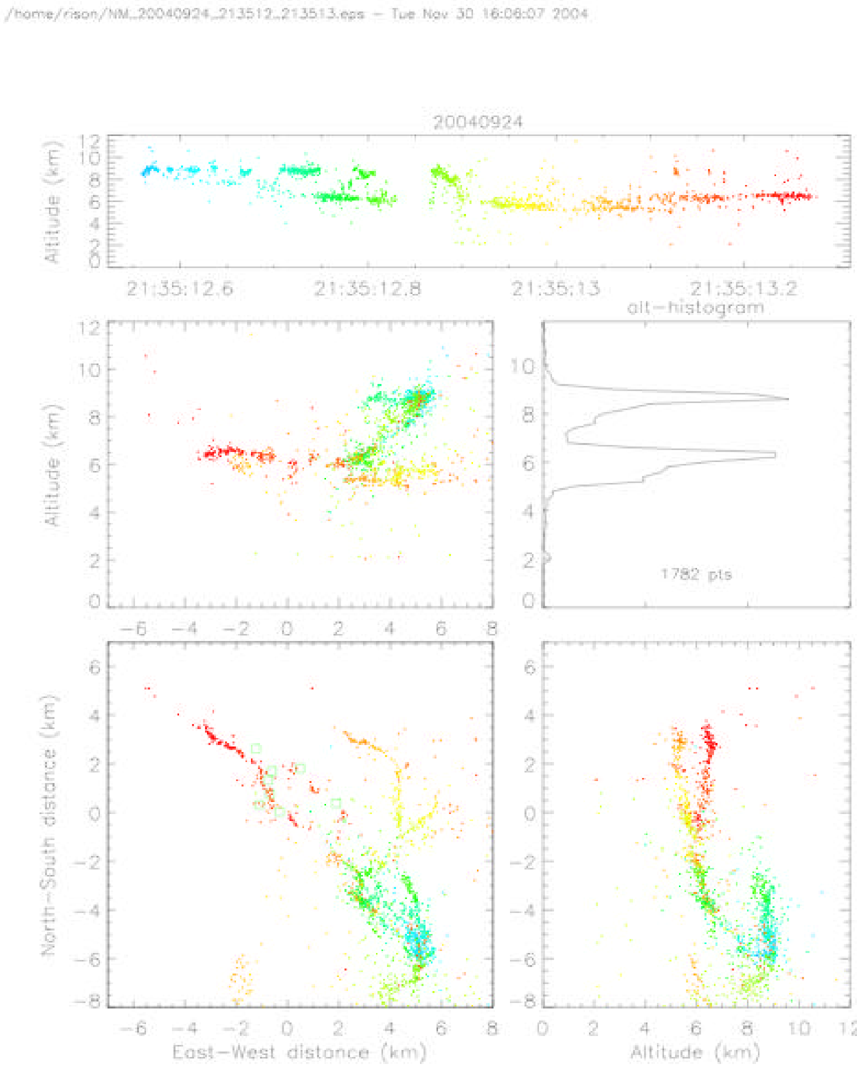

Figure10: A Lightning Flash that began at 2135:12.6 UTC eight kilometers to the southeast of Langmuir Laboratory.

The flash shown in Figure 11 originated only a few kilometers northwest of South Baldy Peak and came to ground within a few hundred meters of South Baldy Peak. Figure 11 shows a North-South elevation that includes this flash and another flash less than two minutes later. Both flashes are visible in the video recording of a TV camera located at the Annex building and pointed at the Balloon Hangar. The TV camera shows that the second flash has two or three separate channels to ground. Lightning flashes with multiple channels to ground are common [*Winn et al.*, 1973].

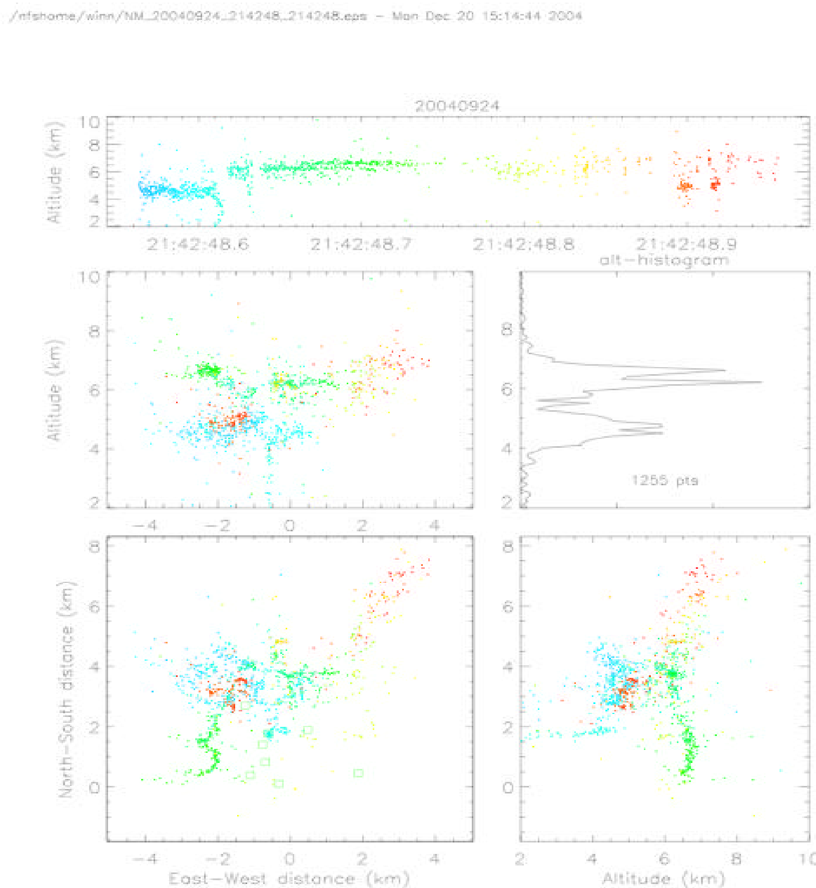

Figure 11: Lightning Flash that began at 2142:48.6 UTC on September 24, 2004. The small squares show the locations of some of the receivers in the Lightning Mapping Array. The northern most receiver shown in this figure is called North Clearing. The closest one to it (to the southeast) is called Kiva, which it near the top of South Baldy Peak. The Kiva receiver is beneath many lightning RF sources from the branch that came to ground nearby.

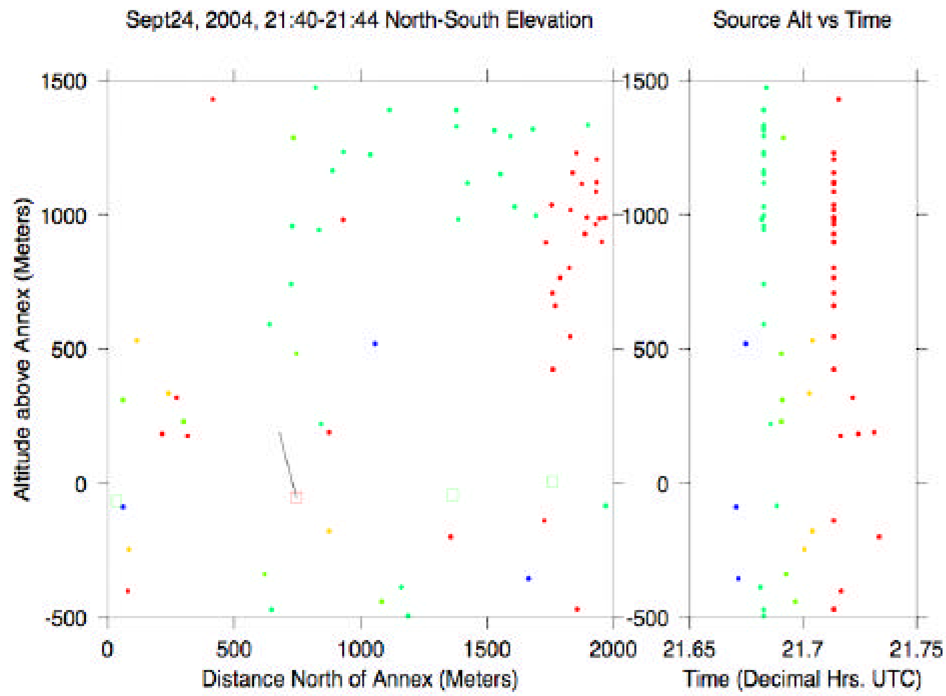

Figure 12: Sources of RF pulses from lightning during the time interval from 2140 to 2144 UTC on September 24, 2004 and located within a cube with edges 2 km long. The left panel shows a projection of the sources onto a north-south vertical plane. The right panel shows the altitudes of the sources *vs*. time. The green dots are for the earlier flash, which, in the TV picture, has two or three channels to ground. The red dots are for the later flash, which the TV picture shows to have hit near the top of South Baldy Peak, the location of the right-hand most green square in the left panel. The squares are LMA receivers—from left to right: Microphone Hill, Balloon Hangar, GWEN, and Kiva.

Figure 13 shows sources of RF radiation from all lightning flashes in a cube with 2 km sides surrounding the Balloon Hangar during a time interval when the electric field was most intense. No lightning flashes were initiated near the Balloon Hangar during this storm, but branches from a few flashes initiated elsewhere passed over the Balloon Hangar.

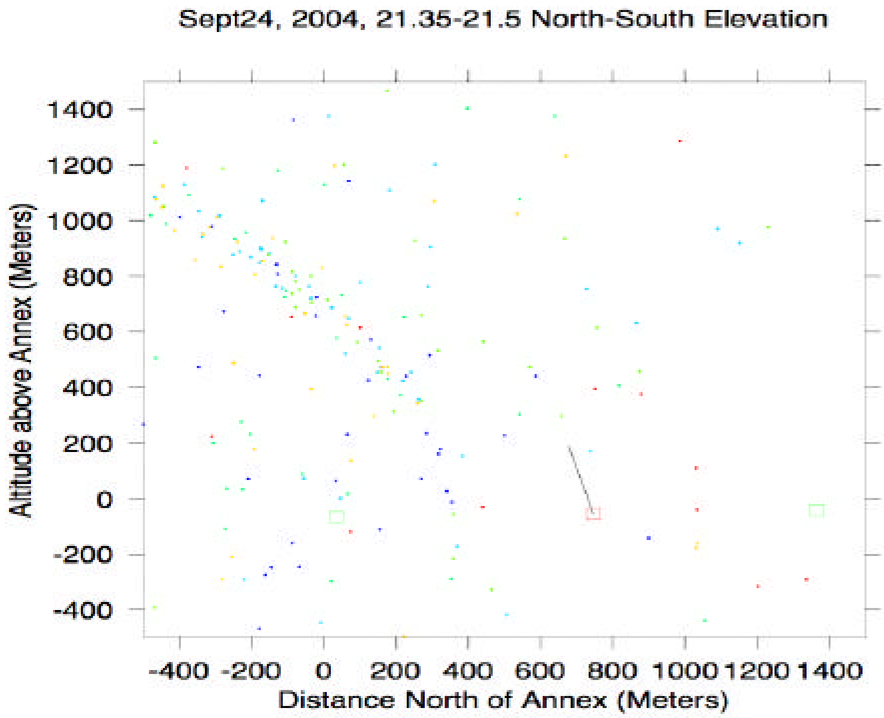

Figure 13: Radio frequency pulses (at 63 MHz) received by the Lightning Mapping Array from 2121 to 2130 UTC during the storm on September 24, 2004.

The location of the filaments in the laser beam is shown as a heavy black line angled 70 above the horizon. The squares are locations of LMA receivers—from left to right: Microphone Hill, Balloon Hangar, and GWEN. The Annex building is at the origin (0,0,0); altitudes are relative to the Annex. To obtain the points on the graph, the largest amplitude signals in each 80 μs interval at each receiver in the array are used to deduce the locations of sources. Then, only the sources inside a 2 km cube surrounding the Balloon Hangar are kept and projected onto the vertical plane depicted.

In an attempt to see if any minor streamers or leaders propagated upward from the top of the laser filaments during a time of intense electric field, we looked at the record of signal strength *vs*. time from the LMA receiver near the Balloon Hangar to see if any signals above the noise were evident at regular 0.1 second intervals. We searched in the time interval from 2124 to 2126 UTC on September 24 when the electric field was above 10 kV/m. The noise during times of intense electric field, as in this time interval, is largely from corona discharges. No effect of the laser filaments could be seen above the corona noise.

5.3 September 25–26

Since the Balloon Hangar and the other facilities along the ridge were engulfed in the cloud this day, the records from the LMA are the best way to determine if lightning flashes near the Hangar were triggered.

The RF lightning sources from the Lightning Mapping Array show that much of the charge in the cloud was at low altitudes—lower than during the usual summer thunderstorms. Figure 1 is an example; lightning began propagating around 6 km above sea level and then propagated at an altitude of about 4 km, which is only 1 km above the ground. Some sources appear to come from very near the ground within 600 meters of the Balloon Hangar.

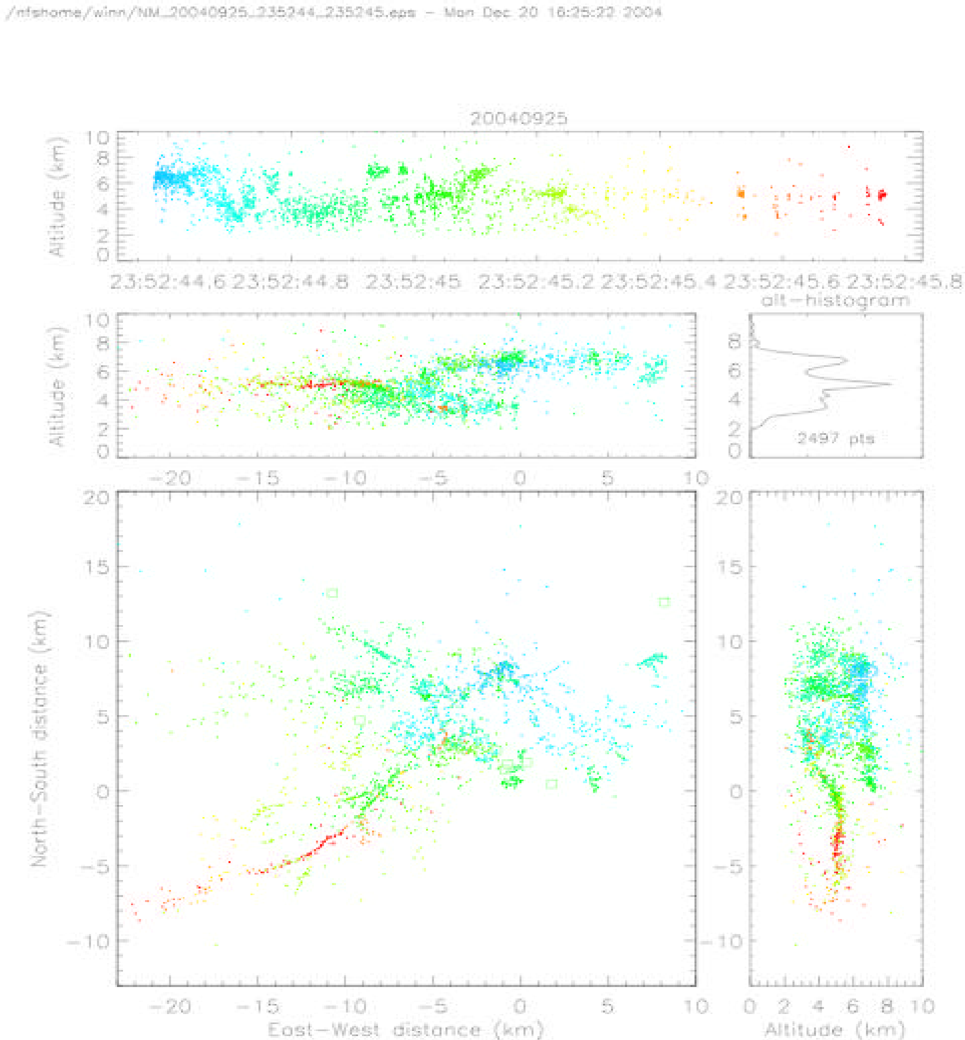

Figure 14: Low altitude lighting flash on September 25, 2004, beginning at 23:52:44.6 UTC. The cloud base was below the altitude of the Balloon Hangar and other Langmuir facilities on the mountain ridge.

Figure 15 shows lightning sources near the Balloon Hangar on September 24 before 2300 UTC and Figure 1 shows lightning sources after 2300 UTC. There are some sources within 600 meters of the Balloon Hangar, but none closer than about 200 m to any part of the laser filaments, which are shown by a black slanted line in the Figures.

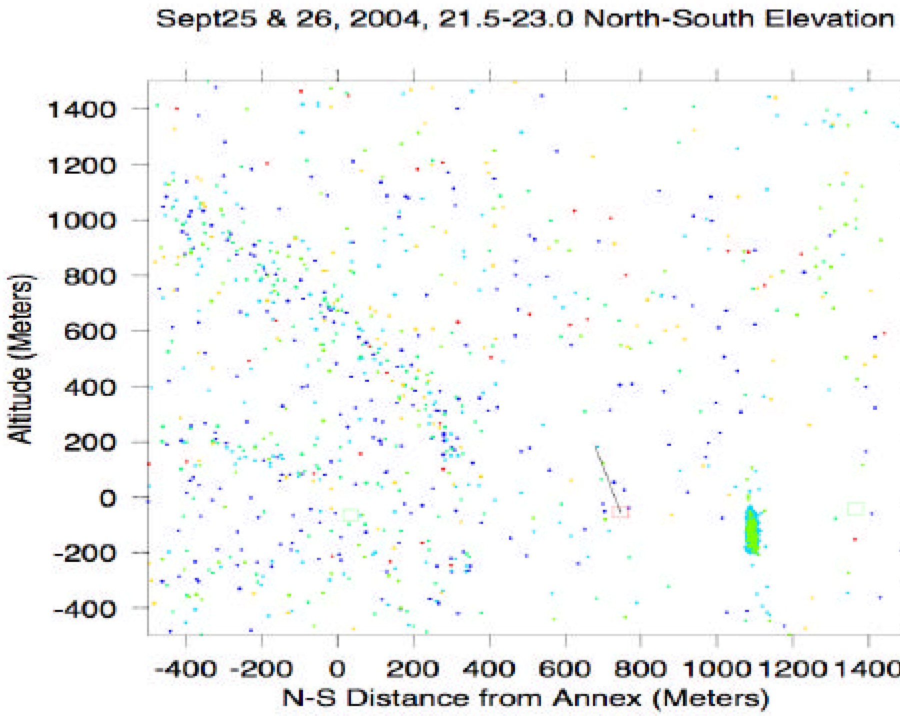

Figure 15: Radio frequency pulses (at 63 MHz) received by the Lightning Mapping Array from 2130 to 2300 UTC on September 26, 2004.

The location of the filaments in the laser beam is shown as a heavy black line angled 70 above the horizon. The radio-frequency sources from lightning that appear to be near the laser filaments are not nearby; they are projections onto the plane of the filaments from distant parallel planes. The squares are locations of LMA receivers; the middle receiver is near the Balloon Hangar. The Annex building is at the origin (0,0,0) and altitudes are relative to the Annex. To obtain the points on the graph, the largest amplitude signals in each 80 μs interval at each receiver in the array are used to deduce the locations of sources. Then, only the sources inside a volume of $2 \times 2 \times 2\ km^3$ surrounding the Balloon Hangar are kept and projected onto the vertical plane depicted. (The dense set of points north of the Balloon Hangar come from an unknown RF source near the ground; the points below ground level are mistakenly placed by the data processing program, probably because the sources were weak and the only LMA receivers that detected them are all near the same altitude.)

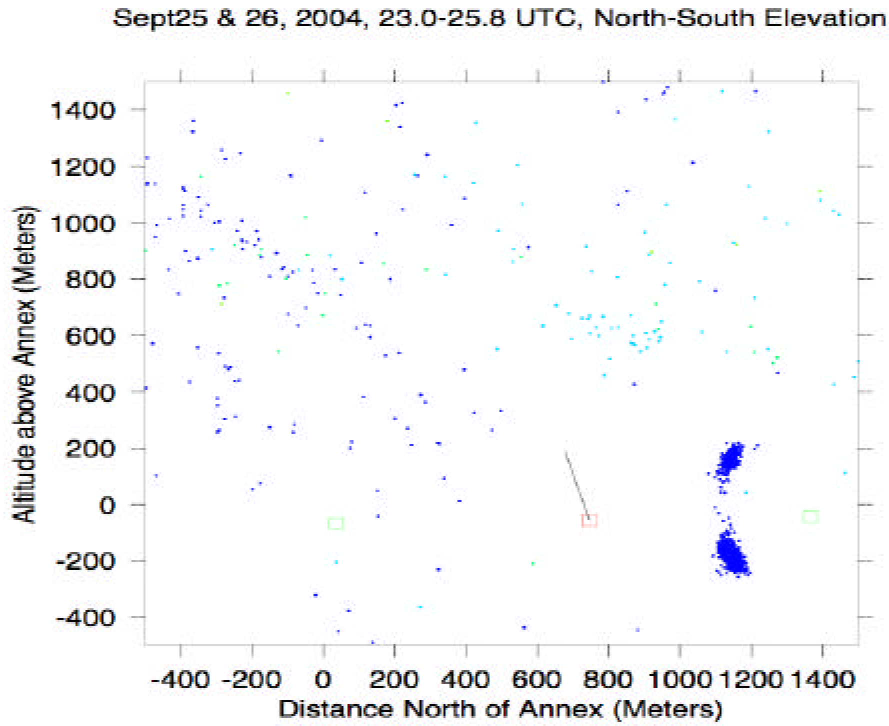

Figure 16: Radio frequency pulses in the time interval following that of the previous figure: from 2300 on September 25 to 0148 UTC on September 26, 2004.

6 Conclusions and Comments

1. The laser filaments did not trigger lightning even though there were times when triggering probably would have been possible with wires hauled up by rockets.
2. We could find no radio frequency emissions or electrical transients that could be ascribed to minor streamers or leaders emanating from the laser filaments.

Apparently, the laser filaments do not establish a good enough conductor for a long enough time to simulate a lightning leader capable of propagating in the rather low electric field amplitudes found below storms.

During this field program there is a good example that illustrates the limitations of protecting facilities by triggering lightning. The natural lightning flash at 2142:48.6 UTC on September 24, 2004, came to ground near Kiva II on South Baldy Peak when the electric field was about -2 kV/m, a value too small for triggering. In general, lightning is capable of propagating to the surface of the earth at locations where the ambient electric field is too low for triggering.

Another documented example comes from a field program in 1999. *Rison et al.*, [2003], describes a lightning flash that began inside a thundercloud and then traveled outside the cloud and hit the ground away from the cloud under blue sky. This kind of flash is called “a bolt from the blue,” (even though it comes from a thundercloud) and it is likely that in flashes of this kind the electric field beside the cloud where lightning struck would be below the threshold for triggering by any means. Triggering to prevent natural lightning flashes, if possible at all, would sometimes need to be carried out at locations distant from the facilities being protected.

A different kind of lightning triggering has been contemplated but not demonstrated: triggering to intercept a downward propagating leader and bring it to earth along the triggering path. This would require exquisite timing or else the maintenance of a continuous conductor by the triggering source, a kind of artificial tower offering protection in an area limited in radius to approximately to the height of the conductor. We do not know where this idea originated.

In spite of the difficulties in practical applications, triggering lightning is a useful technique for studying the properties of lightning and the requirements for its initiation. Laser triggering, if it could be made to work, would provide opportunities not available to triggering by rockets and wires. For example the time delay between the decision to trigger (which could be done automatically with sensors connected to computers) could be much shorter with laser triggering than with rocket triggering. Perhaps a downward propagating leader could be intercepted by a laser beam.

The next step in the development of laser triggering will be to produce a conducting plasma filament that lasts long enough to allow the potential of the earth to be established at the upper end of a filament so that a leader can be launched that can propagate in the relatively low amplitude electric field below thunderstorms.

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